Use of Surface Deflection for Pavement Design and Evaluation

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ABSTRACT

Most current mechanistic pavement design methods are based on strain calculated at the bottom of the asphalt layer and the top of the subgrade. Because the only part of a pavement that is reasonably accessible when construction has been completed is the surface, it is virtually impossible to verify for a design that the parameters have actually been met. The ability of the engineer to check the design will therefore be greatly enhanced if a parameter based on surface deflection can be used. The development of just such a parameter, which has been called the tangent slope, is reported. This parameter is the slope of the tangent drawn from the point of maximum deflection of the pavement to graze its surface. A sensitivity analysis is reported in which the tangent slope is compared with several other parameters based on surface deflection as well as the conventional asphalt and subgrade strains. The calibration by back analysis of the tangent slope against current practice is presented so that it can be used as a design parameter, although its principal use may be as a tool for the structural evaluation of existing pavements and for validating designs.

Mechanistic pavement design techniques for asphalt pavements have been developed to a degree that permits their application with a significant measure of confidence. The Fourth International Conference on the Structural Design of Asphalt Pavements (1) in 1977 was a milestone in the development of these methods; it was devoted almost entirely to the presentation of complete design systems or subsystems. Although mechanistic design is a reality and has been for some years, it is not widely accepted or applied.

One of the reasons for this is the difficulty of checking in the short term that the response of the pavement structure is as predicted. When the principles of structural design are applied to most structural problems, it is relatively easy to check a prediction of the response of the structure against a measured response. Deformation at preselected points is usually a convenient parameter. Mechanistic design of pavements uses response parameters that are difficult to measure. For example, the two most widely used parameters, selected on the basis of a considerable volume of research, are tensile strain at the bottom of the asphalt layer and vertical strain on the subgrade. They are difficult to measure, and so a designer who would like reassurance with regard to the precision of his calculations cannot obtain it.

In addition, pavements are designed for a life measured in terms of many years. Thus traditional validation of mechanistic design methods by full-scale trials will require many years of observation of many pavements.

On both national and international scales, changes in economic conditions have become relatively rapid, and most countries are facing an economic recession. The consequences of this for pavement engineers appear to be that heavy vehicles become heavier and that the resources available for the maintenance of the pavements are decreasing. Thus, in order to maintain and reconstruct the highway network pavement engineers need to use the flexibility in terms of material selection and structural design available to them through the application of mechanistic techniques to flexible pavements.

It is therefore necessary to develop design parameters that can be checked in the traditional manner, by comparing a prediction with a measurement. The only part of a completed pavement readily available for inspection is the surface. So it would seem appropriate to attempt to develop a relationship between pavement life and some characteristics of the deflected shape of the surface of a loaded pavement that is sensitive to structural parameters such as layer thickness and material properties.

Research carried out in an attempt to develop a parameter to meet the requirement of sensitivity based on an analysis of the shape of the surface of a loaded pavement is reported here.

SURFACE DEFLECTION PARAMETERS FOR PAVEMENTS

The best-known surface deflection parameter is the maximum deflection of a point on the surface as measured by the Benkelman beam or similar device. However, the limitations of this single parameter, i.e., that two different pavements may have the same maximum deflection but different deflection profiles, are well known and are shown in Figure 1. Because it is accepted that the strain in the asphalt is an important parameter in the definition of its performance and that this strain is related to the shape of the deflected surface, the inability of a single deflection measurement to differentiate between the two pavements as described earlier is a serious deficiency.

Recognition of this problem has led to the development of several alternative parameters. A literature review undertaken at the start of this research yielded the following parameters:

1. Radius of curvature (R),
2. Deflection ratio (DR),
3. Spreadability (SP),
4. Bending index (BI),
5. Radius of influence (RI), and
6. Slope of deflection (SD).

Formulas for determining these parameters and their sources are presented in Table 1.

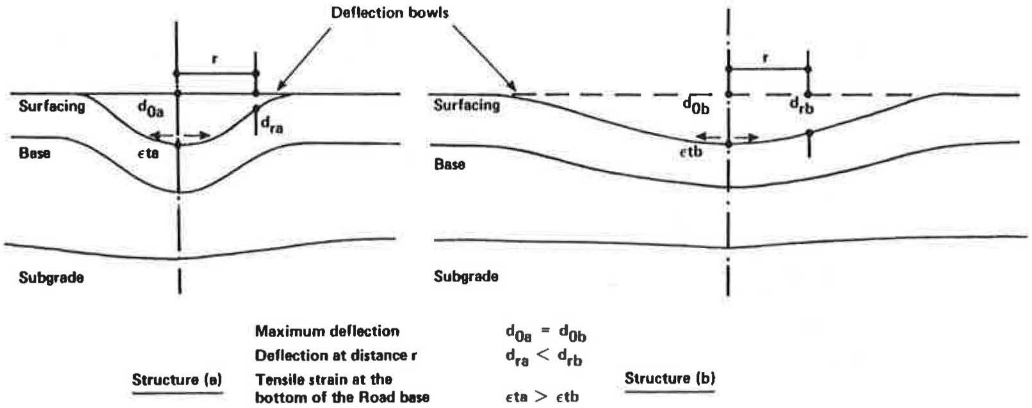


FIGURE 1 Pavements with same maximum deflections but different deflection profiles.

TABLE 1 Parameters Based on Surface Deflection

Parameter	Formula	Source
Radius of curvature[a]	$R = r^2/2d_0[(d_0/d_r) - 1]$	Miura and Tobe *(2)*
Deflection ratio[b]	$DR = d_r/d_0$	Claessen et al. *(3)*
Spreadability[c]	$SP = [(d_0 + d_1 + d_2)/3d_0] \times 100$	Rufford *(4)*
Bending index	$BI = d_0/a$	Hveem *(5)*
Radius of influence	$RI = R^1/d_0$	Ford and Bisselt *(6)*
Slope of deflection[d]	$SD = \tan^{-1}[(d_0 - d_r)/r]$	Kung *(7)*

Note: r = radial distance from center of load; d = deflection (0 = center of load, r = radial distance, 1,2 = locations 1 and 2); a = one-fourth length of deflection basin; R^1 = distance from point of maximum deflection to where curve becomes tangential to horizontal.

[a] r and radius for d_r = 127 mm.

[b] Radius for d_r = 600 mm.

[c] d_1 and d_2 measured at 300 and 600 mm from the load, respectively.

d_r and radius for d_r = 610 mm.

Development

Development of the parameter described in the following is based on the assumption that elastic-layer analysis, which is widely used for mechanistic design, will be used for the prediction. Because elastic-layer analysis provides a reliable representation of the slope of the deflected surface but can be in error with regard to the magnitude of the deflections (R. Koole, unpublished data), it is necessary that parameters developed take account of this. That is, deflection-based parameters should describe the shape of the surface and be independent of the absolute magnitude of the deflection at any point.

Preliminary analysis of pavement structures with the BISTRO (8) program indicated that if a dual-wheel load is considered, the location of the point of maximum deflection is not consistently beneath one of the wheel loads. It could occur between the two. Also, if the locations of the points of maximum deflection at given radii from the load are plotted, they cannot be connected by a straight line, which indicates that near the dual-wheel load the deflected surface has an inconveniently complex shape.

As a result of this preliminary investigation of the surface under dual wheels and because many devices used for pavement evaluation apply loads through one point only, the investigation was restricted to surfaces loaded by one point only.

Definition

Preliminary investigation indicated that the slope of a line drawn outward from the point of maximum deflection to touch but not intersect the surface would meet the requirement of describing the deflected shape and be independent of the absolute magnitude of the deflection.

This line may be considered a tangent to the surface and hence the pavement response parameter has been labeled the tangent slope (TS). Figure 2 shows the parameter.

The tangent slope can be expressed as follows:

$$TS = (dmax - dx)/x \qquad (1)$$

where

dmax = maximum deflection (mm),
dx = deflection at the tangent point (B) (mm), and
x = distance of the tangent point from the point of maximum deflection (m).

CALCULATION PROCEDURE

The procedure for calculating the slope of the tangent is as follows. The deflection of the surface under a dynamic load is measured. A curve to describe the deflected surface is fitted through the measured deflections. This function is then solved simultaneously with the equation of a straight line, the tangent. Because the coordinates of the point of maximum deflection and of the tangent point are known, the slope of the line joining these two points, that is, the tangent slope, can be calculated.

Measurement of Surface Deflection

It is desirable to measure the surface deflection at as many points as possible. This will permit greater flexibility in fitting a curve to the measurements and will provide a more precise curve. However, the device currently available for the measurement of surface deflection has a limited number of sensors, and so for practical reasons it is desirable to define the minimum number of measuring points that will produce satisfactory data. It is also necessary

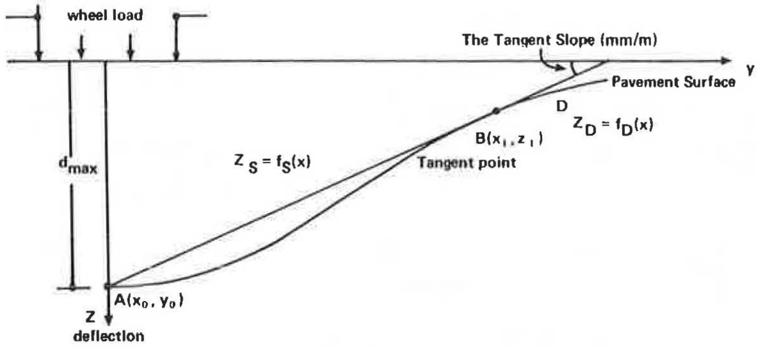


FIGURE 2 Tangent slope.

to obtain some information with regard to the preferred location of the sensor. These two questions were examined by calculating a deflected slope for pavements with a wide range of material properties and layer thicknesses. Sensitivity analyses were then undertaken to assess the effect of measuring deflections at a limited number of points and to define a practical maximum distance from the load for the farthest measuring point.

Deflection profiles were calculated for a large number of pavement structures ranging from relatively flexible layers to stiff ones. This analysis indicated that tangent points would not be more than 1.2 m from the load, which set a practical limit for the location of the farthest measuring point. Because the spacing and number of measuring points are pertinent to fitting a curve to the surface, this will be discussed in the next section.

Fitting a Curve to Deflected Surface

A curve-fitting routine that employs Chebyshev polynomials was selected to represent the deflected surface of the pavement (9). This system has particular advantages in that it can avoid some of the difficulties encountered in solving ill-conditioned simultaneous equations that are sometimes encountered with least-squares curve fitting and also can eliminate situations that may lead to loss of numerical accuracy.

With regard to curve fitting, it is necessary to have data at more points than the order of the polynomial. Ideally the number of measurement points should be at least twice the order of the polynomial; the minimum requirement is one more than the order. Thus for convenience and economy with respect to measuring the surface deflection it is advantageous to determine the lowest-order polynomial that provides a reasonable representation of the shape of the surface. In order to provide information on which to base a decision with respect to the order of polynomial required, the deflection data calculated for several structures were analyzed.

In order to assess goodness of fit the root-mean-square value of the residuals (RMSR) was examined. As the order of the polynomial increases, the RMSR decreases to a fairly constant value. Use of a polynomial with higher order than the first one with the low RMSR will not effectively improve the representation of the data and will increase the risk of unnecessary fluctuations between the data points.

This study examined polynomials of the third, fourth, and fifth order. It was concluded that little improvement in precision was obtained by using functions above the third order. In addition the value of the tangent slope did not change appreciably when the polynomial order was changed. Thus a third-order polynomial should be sufficient for most purposes. This permits a minimum of four measurements of surface deflection for the derivation of the tangent slope. However, reliability and precision will be improved if measurements are made at more points.

In order to calculate the tangent slope it is necessary to locate the tangent point. This is done by using the equation of the curve representing the deflected surface and the equation of the tangent (Equations 2 and 3):

$$Z_d = f_d(x) \tag{2}$$

$$Z_s = f_s(x) \tag{3}$$

The following conditions are necessary for the solution:

1. The slope of the curve at the tangent point must equal the slope of the straight line; i.e., $dz_s/dx = dz_d/dx$ at $x_1 z_1$;
2. The curve must pass through the point x, z: $z_d = z_1 = f_d(x_1)$.

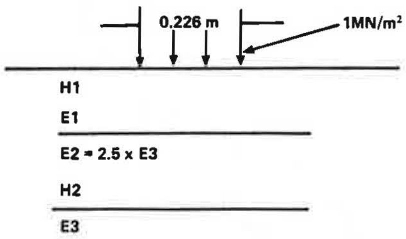
There are two difficulties that may arise when this method is used for calculating the tangent slope. The first is the possibility that more than one tangent point exists. This will be caused by fluctuations between data points when high-order polynomials are used. This difficulty should not arise with the low-order polynomials recommended, and the danger can be further reduced by using more than the minimum number of measurement points.

The second problem may arise if the tangent point is further than 1.2 m from the load. If this is so, the maximum deflection will be small and the tangent slope will not be affected significantly by assuming that the tangent point is 1.2 m from the load.

COMPARISON OF PAVEMENT RESPONSE PARAMETERS

A sensitivity analysis was undertaken to compare various response parameters with the tangent slope. The following parameters were selected from Table 1: radius of curvature, deflection ratio, spreadability, and slope of deflection.

In addition the two commonly used response parameters, tensile strain at the bottom of the bituminous layer (ET) and vertical strain on the subgrade (EV), were included with the maximum resilient deflection (dmax). The sensitivity of these response parameters was investigated with respect to a simple three-layer structure of asphalt, unbound material, and subgrade; the principal structural variables were the thickness of the asphalt, the stiffness of the asphalt, the modulus of the subgrade, and the magnitude of the applied load. Two thicknesses of granular layer, 200 and 700 mm, were also used for the study, but because this variation had little effect on most of the parameters concerned, the results have been omitted from the discussion. In Figure 3 the structures studied are summarized.



H2	0.2		
Parameters / Structures	H1 (m)	E1 (MN/m²)	E3 (MN/m²)
1	A	5000	30
2	0.24	B	30
3	0.24	5000	C
4(D)	0.24	5000	30

A : H1 varied : 0.12, 0.18, 0.24, 0.2, 0.26 m
B : E1 varied : 3000, 5000, 7000, 9000, 1100 MN/m**2
C : E3 varied : 30, 55, 80, 120, 150 MN/m**2
D : Applied stress varied : 0.7, 1.0, 1.35, 1.75, 2.0 MN/m**2

FIGURE 3 Pavement structures used in study of sensitivity of several evaluation parameters.

In order to compare the individual parameters that have a range of dimensions and magnitudes, it was necessary to transform them into dimensionless parameters. This was accomplished by defining the parameter sensitivity (S) as follows:

$$S = [|P_1 - P_i|/P_m] \times 100 \qquad (4)$$

where

P_1 = the first value of the response parameter,
P_i = the ith value of the response parameter, and
P_m = the maximum value of the response parameter for the structural variable under consideration.

This transformation ensures that the parameter sensitivity is always an increasing curve and that no value of S exceeds 100 percent and permits a comparison of the rate of change of the parameter independent of its magnitude. The results of this study are plotted in Figures 4 to 7 and will be discussed in the following.

Thickness of Asphalt Layer

The sensitivity of the various parameters is plotted as a function of the thickness of the asphalt layer in Figure 4. The rate of change of sensitivity of all parameters decreases as the thickness increases. The response parameters are clearly ranked with the tensile strain in the asphalt and the slope of deflection; the tangent slope is the most sensitive and spreadability the least.

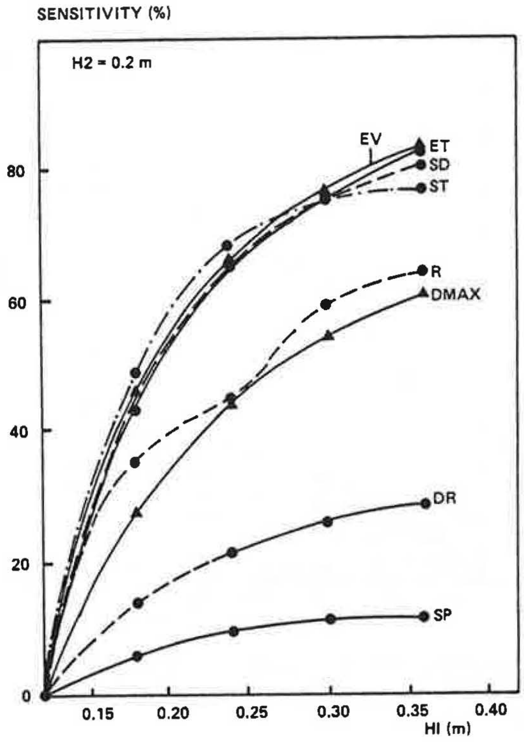


FIGURE 4 Sensitivity as function of asphalt stiffness in structure 1.

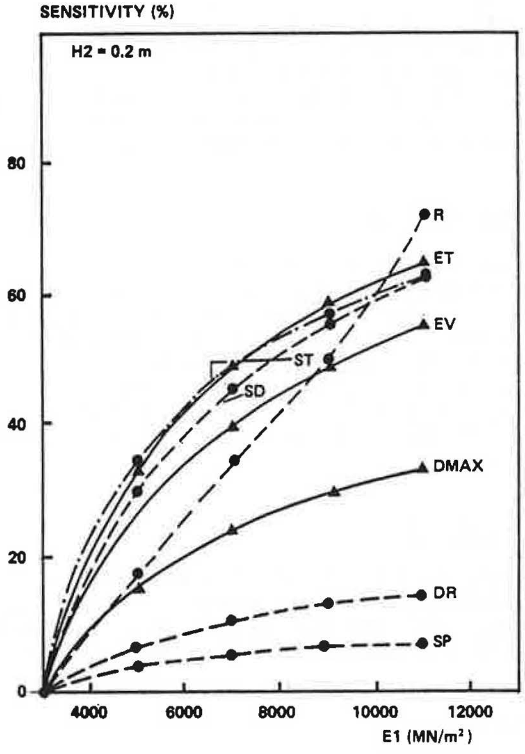


FIGURE 5 Sensitivity as function of asphalt stiffness in structure 2.

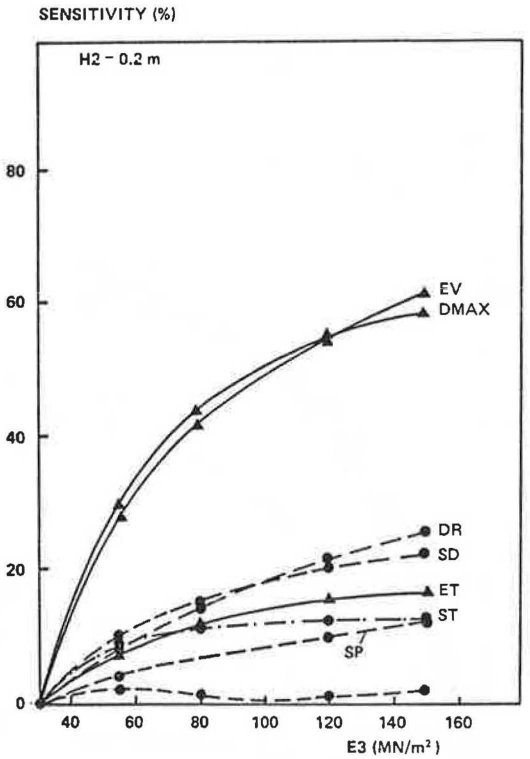


FIGURE 6 Sensitivity as function of subgrade modulus in structure 3.

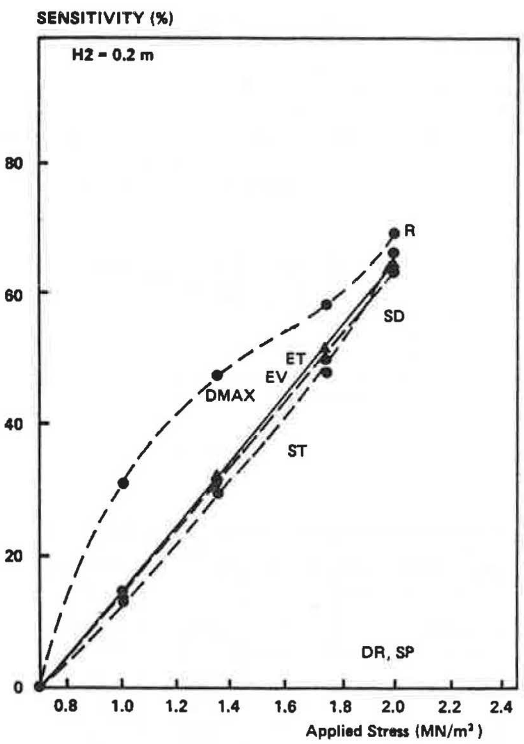


FIGURE 7 Sensitivity as function of applied stress in structure 4.

Stiffness of Asphalt Layer

Figure 5 is a plot of sensitivity as a function of the stiffness of the asphalt layer. With the exception of the radius of curvature, the response parameters are ranked in the same order as those for sensitivity to the asphalt layer thickness, although they tend to fall into distinct groups. The radius of curvature exhibits the useful characteristic of a uniform rate of change with respect to asphalt stiffness and is most sensitive to stiffness at the maximum value selected for this study.

Subgrade Stiffness

The nonlinear model for granular material proposed by Stock and Brown (10) was used for this part of the study. Figure 6 indicates that most parameters are insensitive to variation of subgrade moduli. The exceptions are maximum deflection and the vertical strain on the subgrade. It is particularly noticeable that the radius of curvature hardly changes at all throughout the wide range of subgrade moduli studied.

Applied Stress

As shown in Figure 7, all the parameters calculated show virtually identical sensitivity to the applied load with the exception of the radius of curvature, which is more sensitive except at high stresses.

DISCUSSION

It is clear that none of the eight parameters considered is sensitive to all the structural variables considered. In general spreadability and deflection ratio are insensitive. The two strain parameters are consistently sensitive to the structural parameters investigated, although they are of course difficult to verify in a full-scale structure. Radius of curvature appears to be useful with respect to asphalt thickness and stiffness and applied stress. However, its total insensitivity to subgrade modulus eliminates it as a parameter in its own right.

The tangent slope generally compares well with the other parameters, although it is relatively insensitive to subgrade modulus. However, if it is used in conjunction with maximum deflection, which must be measured in order to calculate the tangent slope, this deficiency is eliminated. An especially successful combination of parameters is radius of curvature and maximum deflection.

CALIBRATION OF TANGENT SLOPE AGAINST CURRENT PRACTICE

In order to improve the value of the tangent slope as a parameter for pavement assessment, it was calibrated against RN29 (11) structures by a process of back analysis. This procedure has been adopted by other research workers and has been widely used for the development of the subgrade strain criteria (12).

RN29 permits three types of base material for pavements: unbound granular material (13), bitumen macadam (14), and hot rolled asphalt (15). Figure 8 is a plot of tangent slope against design life for each of the three types of structures.

CONCLUSIONS

None of the response parameters compared in this study is sensitive to variations in all the possible

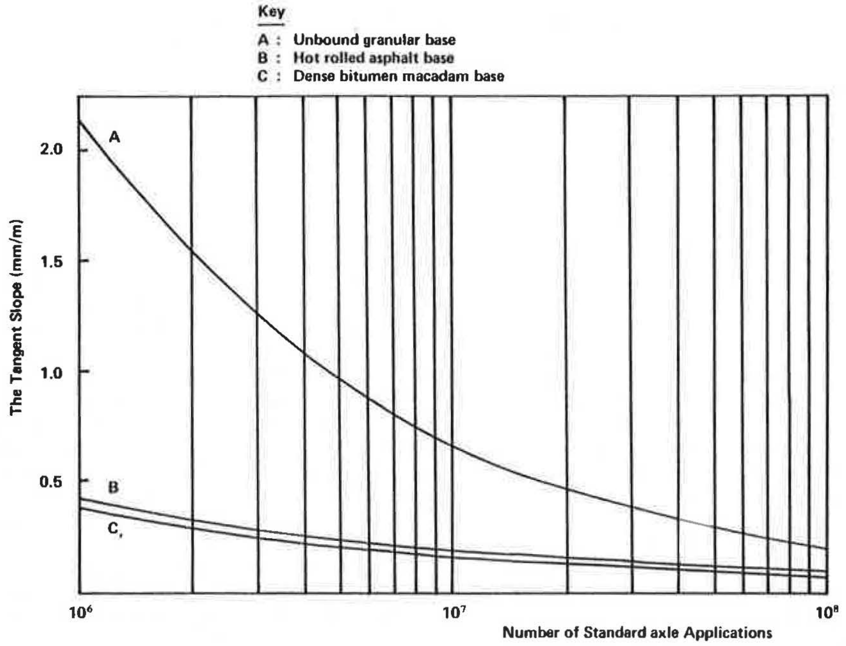


FIGURE 8 Tangent-slope values for typical RN29 structures.

structural parameters in a pavement. The tangent-slope response parameter is adequately sensitive to most structural parameters. It includes variations in both maximum deflection and the shape of the deflected surface and can therefore describe a pavement unambiguously.

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